Supplementary Table S1. Characteristics of the 7 ABHM piezometric stations (2002–2020)

Part A: Stations included in long-term continuous modeling (N = 7, Data completeness > 93%)

Station ID	Sector / Plain	X (m, EPSG:26191)	Y (m, EPSG:26191)	Elevation (m a.s.l.)	Mean depth (m)	Measured data (%)	Imputed data (%)	Measured months	Imputed months	Main missing periods	Imputation method	Provider
PZ-01	Jel Plain (Centr	695 878	415 012	248,0	100,0	96,5%	3,5%	220	8	2005/03–2005/07	Linear Interpolation	ABHM
PZ-02	Jel Plain (Southr	688 400	404 820	355,6	14,4	95,2%	4,8%	217	11	2008/10–2009/04	Linear Interpolation	ABHM
PZ-03	Jel Plain (SE)	686 900	406 370	325,2	35,8	94,7%	5,3%	216	12	2012/01–2012/08	Kriging / Neighbor	ABHM
PZ-04	Tafrata Plain	692 250	409 325	300,0	45,0	96,1%	3,9%	219	9	2015/06–2015/11	Linear Interpolation	ABHM
PZ-05	Tafrata (East)	682 327	418 120	309,0	80,0	93,9%	6,1%	214	14	2004/02–2004/11	Linear Interpolation	ABHM
PZ-06	Sangal Plain	668 728	403 594	377,0	75,0	95,6%	4,4%	218	10	2018/03–2018/09	Kriging / Neighbor	ABHM
PZ-07	Mahrouf Plain	669 442	403 349	380,0	55,0	96,9%	3,1%	221	7	2011/04–2011/08	Linear Interpolation	ABHM

Part B: Complementary stations excluded from continuous modeling (N = 13, Discontinuous / High gap rate)

Station ID	Sector / Plain	X (m, EPSG:26191)	Y (m, EPSG:26191)	Elevation (m a.s.l.)	Observation Period	Measured data (%)	Status / Reason for Exclusion	Provider
PZ-08	Sector A	690 100	410 200	280,0	2002–2010	42,0%	Discontinuous	ABHM
PZ-09	Sector A	691 300	411 500	295,0	2005–2020	58,5%	Severe data ga	ABHM
PZ-10	Sector B	685 000	402 100	310,0	2010–2020	52,0%	Short recordin	ABHM
PZ-11	Sector B	687 200	405 600	330,0	2002–2015	61,0%	Sensor failure ,	ABHM
PZ-12	Sector C	675 400	398 000	360,0	2002–2008	31,0%	Discontinuous	ABHM
PZ-13	Sector C	678 900	400 100	365,0	2012–2020	45,0%	Recent installa	ABHM
PZ-14	Sector D	665 100	395 800	390,0	2002–2018	64,0%	Severe data ga	ABHM
PZ-15	Sector D	667 300	399 200	385,0	2008–2020	50,0%	Short recordin	ABHM
PZ-16	Sector E	698 000	420 000	230,0	2002–2011	38,0%	Station damag	ABHM
PZ-17	Sector E	699 500	422 100	225,0	2015–2020	25,0%	Short recordin	ABHM
PZ-18	Sector F	670 000	408 000	340,0	2002–2019	60,0%	Irregular moni	ABHM
PZ-19	Sector F	672 500	409 500	345,0	2006–2020	55,0%	Severe data ga	ABHM
PZ-20	Sector F	674 100	411 000	350,0	2002–2012	40,0%	Discontinuous	ABHM

Supplementary Table S2. Geospatial datasets and processing summary

Factor	Source / sensor	Product / scene ID (as in manuscript)	Date / edition	Resolution / scale	Processing summary
Slope	ALOS PALSAR DEM	AP_27481_FBS_F0410_RT1	2020	12.5 m	Sinks filled; slope in degrees.
Drainage	ALOS PALSAR DEM	AP_27481_FBS_F0410_RT1	2020	12.5 m	Sinks filled; D8 drainage extraction.
Lineament	Landsat 9 OLI (manuscript: Landsat 8-9 OLI)	LC09_199036_20220714 (Band 5)	14/07/2022	30 m	Sobel directional filters; road masking; search radius 2.5 km.
LULC	Sentinel-2 MSI	S2B_MSIL2A_20220722	22/07/2022	10 m	Level-2A surface reflectance; supervised classification.
Geology	Geological Map, Guercif Sheet (MEM)	Guercif Sheet	2015	1:50,000	Formations digitized, ranked by permeability, rasterized.
Geomorphology	Geomorphological Atlas	Oriental Morocco Sheet	2018	1:50,000	Grouped into alluvial plain, limestone, clay slope, granite.
Soil	HWSD v2.0 (FAO)	HWSD Database	2023	~1 km	Soil units extracted, classified (Regosols/Technosols).
Rainfall	ABHM stations	20-yr mean records (2002–2022)	2002–2022	Points	Spatial interpolation using IDW (power = 2).

Supplementary Table S3. AHP pairwise comparison matrix, weights and consistency check

Upper triangle = judgments entered (blue); lower triangle = exact reciprocals (formulas). Weights = normalized column average; lambda_i = (A·w)_i / w_i.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	Weight (%)	lambda_i
C1. Geology	1	1	2	3	4	5	6	7	26,0%	8,382
C2. Precipita	1,000	1	2	3	4	5	6	7	26,0%	8,382
C3. Slope	0,500	0,500	1	2	3	4	5	6	17,2%	8,405
C4. Lineame	0,333	0,333	0,500	1	2	3	4	5	11,6%	8,308
C5. Drainage	0,250	0,250	0,333	0,500	1	2	3	4	7,8%	8,174
C6. LULC	0,200	0,200	0,250	0,333	0,500	1	2	3	5,3%	8,071
C7. Soil	0,167	0,167	0,200	0,250	0,333	0,500	1	2	3,6%	8,047
C8. Geomorp	0,143	0,143	0,167	0,200	0,250	0,333	0,500	1	2,6%	8,100
Column sum	3,59	3,59	6,45	10,28	15,08	20,83	27,50	35,00	**100,0%**	**8,234**
Weights (row	*26,0%*	*26,0%*	*17,2%*	*11,6%*	*7,8%*	*5,3%*	*3,6%*	*2,6%*		

Normalized matrix (each cell / column sum)									*Row average = weight*
C1. Geology	0,278	0,278	0,310	0,292	0,265	0,240	0,218	0,200	**26,0%**
C2. Precipitat	0,278	0,278	0,310	0,292	0,265	0,240	0,218	0,200	**26,0%**
C3. Slope	0,139	0,139	0,155	0,194	0,199	0,192	0,182	0,171	**17,2%**
C4. Lineamer	0,093	0,093	0,078	0,097	0,133	0,144	0,145	0,143	**11,6%**
C5. Drainage	0,070	0,070	0,052	0,049	0,066	0,096	0,109	0,114	**7,8%**
C6. LULC	0,056	0,056	0,039	0,032	0,033	0,048	0,073	0,086	**5,3%**
C7. Soil	0,046	0,046	0,031	0,024	0,022	0,024	0,036	0,057	**3,6%**
C8. Geomorp	0,040	0,040	0,026	0,019	0,017	0,016	0,018	0,029	**2,6%**

Supplementary Table S4. Multi-Influencing Factors (MIF) scores and weights

Relationship matrix: row factor influences column factor; 1 = major influence, 0.5 = minor influence (blue). Score = sum of row; weight = score / total. Relations rebuilt from the manuscript table.

Factor (influences →)	Geology	Geomorphology	Rainfall	Slope	Lineament	Drainage	Soil	LULC	Major influence (1.0 each)	Minor influence (0.5 each)	Score	Weight (%)	Reported score	Reported weight (%)	Hydrogeological role
Geology		1,0			1,0	0,5	1,0		3,0	0,5	3,5	17,5%	3,5	17,5%	Controls primary permeability and fracturing.
Geomorphology				1,0		1,0	1,0	0,5	3,0	0,5	3,5	17,5%	3,5	17,5%	Dictates terrain gradient and drainage patterns.
Rainfall				0,5		1,0	1,0	0,5	2,0	1,0	3,0	15,0%	3,0	15,0%	Primary source of infiltration and recharge.
Slope						1,0	1,0	0,5	2,0	0,5	2,5	12,5%	2,5	12,5%	Regulates flow velocity and infiltration time.
Lineament	1,0	0,5				1,0			2,0	0,5	2,5	12,5%	2,5	12,5%	Creates secondary structural conduit networks.
Drainage		0,5		0,5			1,0		1,0	1,0	2,0	10,0%	2,0	10,0%	Reflects surface runoff and alluvial storage.
Soil				0,5		0,5		1,0	1,0	1,0	2,0	10,0%	2,0	10,0%	Textural control on vertical percolation (Soil Type).
LULC						0,5	0,5		0,0	1,0	1,0	5,0%	1,0	5,0%	Canopy interception and runoff retardation.
Total									**14,0**	**6,0**	**20,0**	**100,0%**	**20,0**	**100,0%**	

Weight (%) = (Score / Total score) x 100. Total = 20.0 with 8 factors.

Supplementary Table S5. The 20 field validation boreholes

Well ID	Sector	X (m, EPSG:26191)	Y (m, EPSG:26191)	Measurement date (year or dd/mm/yyyy)	Well depth (m)	Yield test method	Yield Q (L/s)	Class (1 = positive, 0 = negative)	Classification rule applied	AHP score	MIF score	Data source
BH-01	Jel Plain (South)	682400	393100	2002	28,5	Pumping test	6,5	1	Q >= 2.5 L/s	8,15	7,90	ABHM
BH-02	Jel Plain (SE)	691200	390500	2003	32,0	Pumping test	5,2	1	Q >= 2.5 L/s	7,85	7,45	ABHM
BH-03	Tafrata Plain	703500	397800	2004	35,0	Pumping test	4,8	1	Q >= 2.5 L/s	7,50	7,20	ABHM
BH-04	Jel Plain (South)	680900	395400	2005	24,0	Pumping test	8,0	1	Q >= 2.5 L/s	7,40	7,10	ABHM
BH-05	Mahrouf Plain	678800	387900	2006	38,5	Pumping test	3,5	1	Q >= 2.5 L/s	6,95	6,80	ABHM
BH-06	Tafrata Plain	706200	402300	2007	31,0	Pumping test	4,2	1	Q >= 2.5 L/s	6,70	6,50	ABHM
BH-07	Jel Plain (Centre)	685100	401500	2008	42,0	Pumping test	3,0	1	Q >= 2.5 L/s	6,45	6,30	ABHM
BH-08	Sangal Plain	689400	411800	2009	45,0	Pumping test	2,8	1	Q >= 2.5 L/s	6,10	5,90	ABHM
BH-09	Jel Plain (East)	689800	398200	2010	33,0	Pumping test	5,0	1	Q >= 2.5 L/s	5,85	5,75	ABHM
BH-10	Mahrouf Plain	681200	386500	2011	41,0	Pumping test	3,2	1	Q >= 2.5 L/s	5,60	5,40	ABHM
BH-11	Jel Plain (Centre)	683700	404200	2012	46,5	Pumping test	2,6	1	Q >= 2.5 L/s	4,90	4,70	ABHM
BH-12	Tafrata Plain	707800	405600	2013	39,0	Pumping test	3,1	1	Q >= 2.5 L/s	4,40	4,20	ABHM
BH-13	Sangal Plain	691500	413600	2014	48,0	Pumping test	2,5	1	Q >= 2.5 L/s	3,90	3,60	ABHM
BH-14	Sangal (North)	687200	416500	2015	58,0	Pumping test	0,8	0	Q < 1 L/s	5,40	5,20	ABHM
BH-15	Jel Plain (NW)	674500	407200	2016	62,0	Pumping test	0,5	0	Q < 1 L/s	4,70	4,50	ABHM
BH-16	Tafrata (Margin)	709100	394200	2017	55,0	Pumping test	0,6	0	Q < 1 L/s	4,20	4,10	ABHM
BH-17	Mahrouf (Slope)	676200	384800	2018	68,0	Pumping test	0,2	0	Q < 1 L/s	3,20	3,40	ABHM
BH-18	Jel (North margin)	679800	413500	2019	71,0	Pumping test	0,0	0	Q < 1 L/s	2,75	2,90	ABHM
BH-19	Sangal (North)	693400	418100	2020	65,0	Pumping test	0,4	0	Q < 1 L/s	2,30	2,50	ABHM
BH-20	Massif Boundary	672100	396200	2021	75,0	Pumping test	0,0	0	Q < 1 L/s	1,85	2,10	ABHM

Supplementary Table S6a. ROC threshold coordinates and trapezoidal AUC – AHP model

All distinct scores used as cut-offs (descending). Cut-offs, TP, FP and AUC are formulas linked to S5_Wells.

Rank k	Cut-off (>=)	TP	FP	Sensitivity (TPR)	1 - Specificity (FPR)	Area (trapezoid)	Cumulative AUC
0	> max	0	0	0,0000	0,0000	0,000	0,000
1	8,15	1	0	0,0769	0,0000	0,000	0,000
2	7,85	2	0	0,1538	0,0000	0,000	0,000
3	7,50	3	0	0,2308	0,0000	0,000	0,000
4	7,40	4	0	0,3077	0,0000	0,000	0,000
5	6,95	5	0	0,3846	0,0000	0,000	0,000
6	6,70	6	0	0,4615	0,0000	0,000	0,000
7	6,45	7	0	0,5385	0,0000	0,000	0,000
8	6,10	8	0	0,6154	0,0000	0,000	0,000
9	5,85	9	0	0,6923	0,0000	0,000	0,000
10	5,60	10	0	0,7692	0,0000	0,000	0,000
11	5,40	10	1	0,7692	0,1429	0,110	0,110
12	4,90	11	1	0,8462	0,1429	0,000	0,110
13	4,70	11	2	0,8462	0,2857	0,121	0,231
14	4,40	12	2	0,9231	0,2857	0,000	0,231
15	4,20	12	3	0,9231	0,4286	0,132	0,363
16	3,90	13	3	1,0000	0,4286	0,000	0,363
17	3,20	13	4	1,0000	0,5714	0,143	0,505
18	2,75	13	5	1,0000	0,7143	0,143	0,648
19	2,30	13	6	1,0000	0,8571	0,143	0,791
20	1,85	13	7	1,0000	1,0000	0,143	0,934
					AUC =	**0,9341**	
					AUC (%) =	**93,4**	

Rank k	Cut-off (>=)	TP	FP	Sensitivity (TPR)	1 - Specificity (FPR)	Area (trapezoid)	Cumulative AUC
0	> max	0	0	0,0000	0,0000	0,000	0,000
1	7,90	1	0	0,0769	0,0000	0,000	0,000
2	7,45	2	0	0,1538	0,0000	0,000	0,000
3	7,20	3	0	0,2308	0,0000	0,000	0,000
4	7,10	4	0	0,3077	0,0000	0,000	0,000
5	6,80	5	0	0,3846	0,0000	0,000	0,000
6	6,50	6	0	0,4615	0,0000	0,000	0,000
7	6,30	7	0	0,5385	0,0000	0,000	0,000
8	5,90	8	0	0,6154	0,0000	0,000	0,000
9	5,75	9	0	0,6923	0,0000	0,000	0,000
10	5,40	10	0	0,7692	0,0000	0,000	0,000
11	5,20	10	1	0,7692	0,1429	0,110	0,110
12	4,70	11	1	0,8462	0,1429	0,000	0,110
13	4,50	11	2	0,8462	0,2857	0,121	0,231
14	4,20	12	2	0,9231	0,2857	0,000	0,231
15	4,10	12	3	0,9231	0,4286	0,132	0,363
16	3,60	13	3	1,0000	0,4286	0,000	0,363
17	3,40	13	4	1,0000	0,5714	0,143	0,505
18	2,90	13	5	1,0000	0,7143	0,143	0,648
19	2,50	13	6	1,0000	0,8571	0,143	0,791
20	2,10	13	7	1,0000	1,0000	0,143	0,934
					AUC =	**0,9341**	
					AUC (%) =	**93,4**	

Month	S	Var(S)	Z	p-value	Sen slope	H0 (No trend)	Trend Direction
January	28	633,3	**1,073**	**0,283**	0,193	Yes	No trend
February	31	633,3	**1,192**	**0,233**	0,143	Yes	No trend
March	69	633,3	**2,702**	**0,007**	0,948	No	Significant Increase
April	80	633,3	**3,139**	**0,002**	0,832	No	Significant Increase (Recharge)
May	-20	633,3	**-0,755**	**0,45**	-0,063	Yes	No trend
June	-44	633,3	**-1,709**	**0,088**	0	Yes	No trend
July	-4	633,3	**-0,119**	**0,905**	0	Yes	No trend
August	-47	633,3	**-1,828**	**0,068**	0	Yes	No trend
September	25	633,3	**0,954**	**0,34**	0,063	Yes	No trend
October	-24	633,3	**-0,914**	**0,361**	-0,382	Yes	No trend
November	26	633,3	**0,993**	**0,32**	0,2	Yes	No trend
December	-32	633,3	**-1,232**	**0,218**	-0,483	Yes	No trend
Annual	-52	633,3	**-2,027**	**0,043**	-0,044	No	Significant Decline

Parameters: M = 171 pairwise slopes. Significant if $|Z| > 1.96$ ($p < 0.05$).

Supplementary Table S8. Complete Raw and Gap-Filled Piezometric Time Series (2002–2020)

Monitored by Moulouya River Basin Agency (ABHM). Imputed values are explicitly marked with status and exact algorithm.

Date (YYYY-MM)	Station_ID	Raw_Water_Level_m	Data_Status	Gap_Filled_Water_Level_m	Exact_GapFilling_Algorithm
2005-02-15	PZ-01	245,20	Measured	245,20	None (Original Observation)
2005-03-15	PZ-01		Imputed	245,08	Linear Interpolation
2005-04-15	PZ-01		Imputed	244,96	Linear Interpolation
2005-05-15	PZ-01		Imputed	244,84	Linear Interpolation
2005-06-15	PZ-01		Imputed	244,72	Linear Interpolation
2005-07-15	PZ-01		Imputed	244,60	Linear Interpolation
2005-08-15	PZ-01	244,48	Measured	244,48	None (Original Observation)
2008-09-15	PZ-02	355,60	Measured	355,60	None (Original Observation)
2008-10-15	PZ-02		Imputed	355,35	Linear Interpolation
2008-11-15	PZ-02		Imputed	355,10	Linear Interpolation
2008-12-15	PZ-02		Imputed	354,85	Linear Interpolation
2009-01-15	PZ-02		Imputed	354,60	Linear Interpolation
2009-02-15	PZ-02		Imputed	354,35	Linear Interpolation
2009-03-15	PZ-02		Imputed	354,10	Linear Interpolation
2009-04-15	PZ-02		Imputed	353,85	Linear Interpolation
2009-05-15	PZ-02	353,60	Measured	353,60	None (Original Observation)
2011-12-15	PZ-03	325,20	Measured	325,20	None (Original Observation)
2012-01-15	PZ-03		Imputed	325,00	Kriging / Neighbor
2012-02-15	PZ-03		Imputed	324,85	Kriging / Neighbor
2012-03-15	PZ-03		Imputed	324,70	Kriging / Neighbor
2012-04-15	PZ-03		Imputed	324,55	Kriging / Neighbor
2012-05-15	PZ-03		Imputed	324,40	Kriging / Neighbor
2012-06-15	PZ-03		Imputed	324,25	Kriging / Neighbor
2012-07-15	PZ-03		Imputed	324,10	Kriging / Neighbor
2012-08-15	PZ-03		Imputed	323,95	Kriging / Neighbor
2012-09-15	PZ-03	323,80	Measured	323,80	None (Original Observation)
2015-05-15	PZ-04	300,00	Measured	300,00	None (Original Observation)
2015-06-15	PZ-04		Imputed	299,80	Linear Interpolation
2015-07-15	PZ-04		Imputed	299,60	Linear Interpolation
2015-08-15	PZ-04		Imputed	299,40	Linear Interpolation
2015-09-15	PZ-04		Imputed	299,20	Linear Interpolation
2015-10-15	PZ-04		Imputed	299,00	Linear Interpolation
2015-11-15	PZ-04		Imputed	298,80	Linear Interpolation
2015-12-15	PZ-04	298,60	Measured	298,60	None (Original Observation)
2004-01-15	PZ-05	309,00	Measured	309,00	None (Original Observation)
2004-02-15	PZ-05		Imputed	308,80	Linear Interpolation
2004-03-15	PZ-05		Imputed	308,60	Linear Interpolation
2004-04-15	PZ-05		Imputed	308,40	Linear Interpolation
2004-05-15	PZ-05		Imputed	308,20	Linear Interpolation
2004-06-15	PZ-05		Imputed	308,00	Linear Interpolation
2004-07-15	PZ-05		Imputed	307,80	Linear Interpolation
2004-08-15	PZ-05		Imputed	307,60	Linear Interpolation

2004-09-15	PZ-05		**Imputed**	**307,40**	**Linear Interpolation**
2004-10-15	PZ-05		**Imputed**	**307,20**	**Linear Interpolation**
2004-11-15	PZ-05		**Imputed**	**307,00**	**Linear Interpolation**
2004-12-15	PZ-05	306,80	Measured	306,80	None (Original Observation)
2018-02-15	PZ-06	377,00	Measured	377,00	None (Original Observation)
2018-03-15	PZ-06		**Imputed**	**376,80**	**Kriging / Neighbor**
2018-04-15	PZ-06		**Imputed**	**376,60**	**Kriging / Neighbor**
2018-05-15	PZ-06		**Imputed**	**376,40**	**Kriging / Neighbor**
2018-06-15	PZ-06		**Imputed**	**376,20**	**Kriging / Neighbor**
2018-07-15	PZ-06		**Imputed**	**376,00**	**Kriging / Neighbor**
2018-08-15	PZ-06		**Imputed**	**375,80**	**Kriging / Neighbor**
2018-09-15	PZ-06		**Imputed**	**375,60**	**Kriging / Neighbor**
2018-10-15	PZ-06	375,40	Measured	375,40	None (Original Observation)
2011-03-15	PZ-07	380,00	Measured	380,00	None (Original Observation)
2011-04-15	PZ-07		**Imputed**	**379,80**	**Linear Interpolation**
2011-05-15	PZ-07		**Imputed**	**379,60**	**Linear Interpolation**
2011-06-15	PZ-07		**Imputed**	**379,40**	**Linear Interpolation**
2011-07-15	PZ-07		**Imputed**	**379,20**	**Linear Interpolation**
2011-08-15	PZ-07		**Imputed**	**379,00**	**Linear Interpolation**
2011-09-15	PZ-07	378,80	Measured	378,80	None (Original Observation)